High Speed Cryogenic Drilling of Grade 5 ELI Titanium Alloy

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Abstract

Titanium is one of the most important materials, with almost 80% of Ti-6Al-4V being used in the aerospace industry. Drilling of titanium parts is one of the dominant processes in this industry. However, there are very limited studies on the effect of machining environments such as flood, MQL and cryogenic cooling in drilling titanium. This paper addresses this gap by investigating the effects of various machining environment in drilling titanium. Numerical modelling and experimental analysis showed that at high cutting speeds, cryogenic cooling can significantly reduce cutting temperature and therefore chemical affinity between cutting tool and workpiece materials. Cryogenic cooling resulted in minimised tool wear as compared to MQL and flood cooling. Furthermore, 43% reduction in average surface roughness was achieved using cryogenic cooling.

1. Introduction

Drilling is one of the major manufacturing processes for making holes and is usually conducted on semi-finished parts prior to assembly. Therefore, poor quality drilling operations can be very costly resulting in scrapping parts which has already gone through a number of value adding processes. This is particularly important for parts manufactured by near net shape processes such as additive manufacturing/3D printing, casting and extrusion. The uptake of additive manufacturing for metal parts and specifically difficult to machine materials such as Ti-6Al-4V titanium alloy, Inconel 718 nickel alloys and stainless and maraging steel has increased the importance of processes such as drilling, tapping and reaming.

Drilling forms 40% to 60% of the total subtractive processes [1] and is of specific importance in aerospace industries. The target values for reducing fuel consumption, CO_2 emission, NO_x emission and noise level [2] have driven aerospace industries to increase the use of advanced materials such as titanium, nickel and cobalt alloys and composites in aircrafts. These objectives require using heat resistant alloys which are stronger and can withstand higher temperatures [3]. Ti-6Al-4V alpha-beta titanium alloy is the most dominant titanium alloy [4], 80% of which is used in aerospace and medical industries. It has the highest strength to weight ratio among structural materials and can withstand temperatures as high as 400ºC making it an ideal candidate for aerospace applications [5].

Ti-6Al-4V consists of alpha phase with hexagonal closed pack (hcp) lattice structure and beta phase with body centred cubic (bcc) lattice structure. The hcp lattice in Ti-6Al-4V alloy has limited slip planes which allows slip on the basal plane (0001) along the <1120> direction. Moreover, deformation twining can take place under extreme cutting pressures which can further complicate the machining of this alloy. The Combination of hcp and bcc lattices in alpha and beta structures has resulted in high material strength, hardness and the strength strain hardening tendency of Ti-6Al-4V which have made this titanium alloy notoriously difficult to machine [6, 7]. Titanium is chemically reactive to all known cutting tool materials leading to diffusion and adhesion tool wear mechanisms during machining operations.

Material strength and hardness of titanium alloys results in excessive heat generation during machining operations. Poor thermal conductivity of the material prevents effective heat dissipation through workpiece and cutting chips resulting in high localised temperatures at the cutting zone [8]. Controlling heat generation through precise selection of cutting parameters [9] and use of high pressure cutting fluids [10] are recommended for machining titanium. Cryogenic cooling, using liquid nitrogen as an alternative cutting fluid, has been investigated by various authors as a method for improving machinability of difficult-to-machine materials [5, 11, 12]. At cryogenic temperatures, the beta phase of Ti-6Al-4V alloy undergoes a ductile-to-brittle transition. Moreover, low temperatures reduce the chemical reactivity of titanium alloy further improving the machinability. Cryogenic cooling has shown significant potential to enhance surface integrity and reduce surface roughness, improve tool life and allow for higher material removal rates

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[5, 13]. The latter is particularly important as it will increase the throughput of aerospace and medical industries where machining titanium is often considered a manufacturing bottleneck.

Park et al. [14] investigated the effect of various cooling condition in end milling Ti-6Al-4V titanium alloy and concluded that up to 93% reduction in tool wear can be achieved using cryogenic cooling as compared to dry machining. The authors studied the use of external cryogenic nozzle and through the spindle cryogenic cooling technique and also combination of MQL and cryogenic cooling. The lowest tool wear was reported to be from the combination of MQL and cryogenic cooling. Biermann et al. [15] reported that combination of CO_2 cryogenic cooling with MQL can significantly improve the machinability of Ti-6Al-2Sn-4Zr-6Mo alpha beta titanium alloy in turning operations. In turning porous tungsten, Schoop et al. [16] reported that cryogenic cooling can considerably improve the surface integrity of the machined test pieces and result in improved surface roughness. Bordin et al. [12] investigated the effect of cryogenic cooling in turning electron beam melting (EBM) additively manufactured Ti-6Al-4V titanium alloy. They observed that cryogenic cooling results in reduced adhesion of workpiece material onto the cutting tool and therefore can improve tool life.

An overview of academic literature indicated that there is a lack of study on cryogenic drilling processes. The aim of this study is to identify the feasibility of using an external nozzle for high speed cryogenic drilling of Ti-6Al-4V titanium alloy. In order to compare the results, the drilling experiments are also repeated using conventional flood cooling and minimum quantity lubricant (MQL) method.

2. Methodology

This research consisted of two phases namely, finite element modeling (FEA) of the process and experimental evaluation. Deform 3D was used to simulate the machining process which is further discussed in section 3. Three blocks of titanium with 150mmx50mmx50mm were prepared for machining experiment. A 10mm diameter twisted drill with 4mm web thickness, 30º helix angle and 135º point angle made from solid tungsten carbide with 10% cobalt binder was used for each experiment. The machining parameters are presented in table 1. The experiments were conducted under flood cooling, MQL and cryogenic cooling using liquid nitrogen coolant. They consisted of drilling 10mm diameter holes with 25mm depth and the experiments were continued until tool failure. After machining experiments, the surface roughness of the holes was measured using a contact method with 50nm diamond probe. For surface roughness measurements, 5x0.8mm cut offs were used. The cutting tools were examined using scanning electron microscope (SEM) and the micrographs of the cutting tools were generated. The details of the experimental results are presented in section 4.

Table 1: Cutting parameters used for drilling experiments

Cutting speed	Spindle speed	Feed rate	Feed rate	Depth
110m/min	3501rpm	0.06mm/revolution	210.06mm/min	25mm

3. FEA Modelling of Drilling

Johnson-Cook constitutive model shown in equation 1 was used for simulating the material behavior in drilling process [17]. It is a widely used model for simulating high strain rate processes such as machining [18].

$$\bar{\sigma} = (A + B\bar{\varepsilon}^n)\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_m - T_{room}}\right)^m\right] \quad (1)$$

where, $\bar{\sigma}$ = equivalent plastic stress, $\bar{\varepsilon}$ = equivalent plastic strain, $\dot{\bar{\varepsilon}}$ = plastic strain rate, $\dot{\bar{\varepsilon}}_0$ = reference plastic strain rate, T = temperature, T_{room} = room temperature, T_m = material melting temperature and A, B, C, m and n are material specific parameters.

The Johnson-Cook model parameters used for this study are provided in table 2. A 3D model of the drill bit was developed based on the real drill geometry described in methodology section. The cutting parameters described in table 1 were used for developing the computational model. The model was run for 500 steps for each machining environment and the results were compared. Figure 1 illustrates the predicted temperature of the drill bit for each machining environment.

Table 2: Johnson-Cook constitutional material model parameters for Ti-6Al-4V

Johnson-Cook Parameter	Value
A	896MPa
B	656MPa
C	0.0128
m	0.8
n	0.5
$\dot{\bar{\varepsilon}}_0$	$1 sec^{-1}$
T_m	1660ºC

The simulation indicated that the highest cutting temperature took place at the tip of the drill on the rake face where the cutting chips flow irrespective of the machining environment. Furthermore, as shown in figure 1, flood cooling produced the highest cutting temperature of 1150ºC as compared to 868ºC for MQL and 725ºC for cryogenic machining environment. This indicates that cryogenic cooling has reduced the cutting temperature by 37% as compared to flood cooling. Furthermore, the lubrication effect of MQL has reduced heat generation due to friction resulting in 25% lower cutting temperature as opposed to flood cooling.

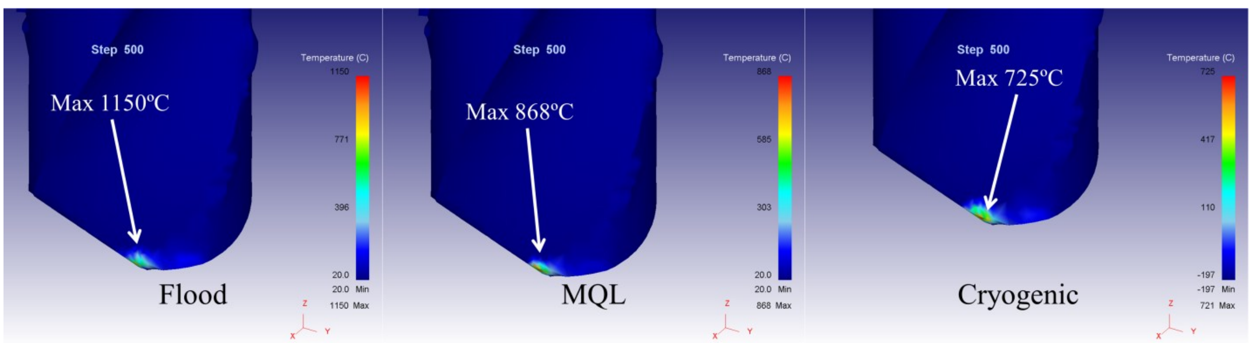

Figure 1: FEA simulation of cutting temperature in drilling Ti-6Al-4V alloy using different machining environments

4. Results of Surface Roughness and Tool Wear

The drilling experiments were conducted under flood, MQL and cryogenic conditions and the surface roughness of the generated holes was measured as explained in the methodology section. The surface roughness was measured 3 times for each hole and the average surface roughness was calculated to represent the surface roughness of the hole.

Figure 2 demonstrates the average surface roughness of each hole generated for various machining environment. Comparing the average surface roughness of the holes for MQL environment was 3.3µm showing no significant difference with 3.35µm for flood cooling. The lowest surface roughness was produced using cryogenic cooling where 1.92µm average surface roughness was measured. However, analyzing the graph for surface roughness of individual holes shown in figure 2 indicates that there is a significant difference between results from MQL and flood cooling environments. Since, a new drilling tool was used for each drilling experiment, it is a valid assumption to assume no tool wear was present for drilling the first hole of each machining environment. Comparing the surface roughness of the first hole of each machining experiment, indicates that the surface roughness for MQL is 35% higher than that of flood cooling. Similarly, the surface roughness of the first hole from flood cooling is only 7% higher than that of cryogenic machining environment. Apart from the results from cryogenic experiment, an increasing trend in surface roughness is evident when the number of holes and therefore tool wear is increased. This would clearly explain the fact that cryogenic cooling resulted in lower average surface roughness. The effect of cryogenic cooling on improving surface integrity has been reported by [13] and [19] in end milling and turning operations. This study indicated that these results can be extended to drilling operations using an external nozzle. However, as mentioned above, the effectiveness of the process is more limited than turning and milling where there is a line of sight into the cutting zone.

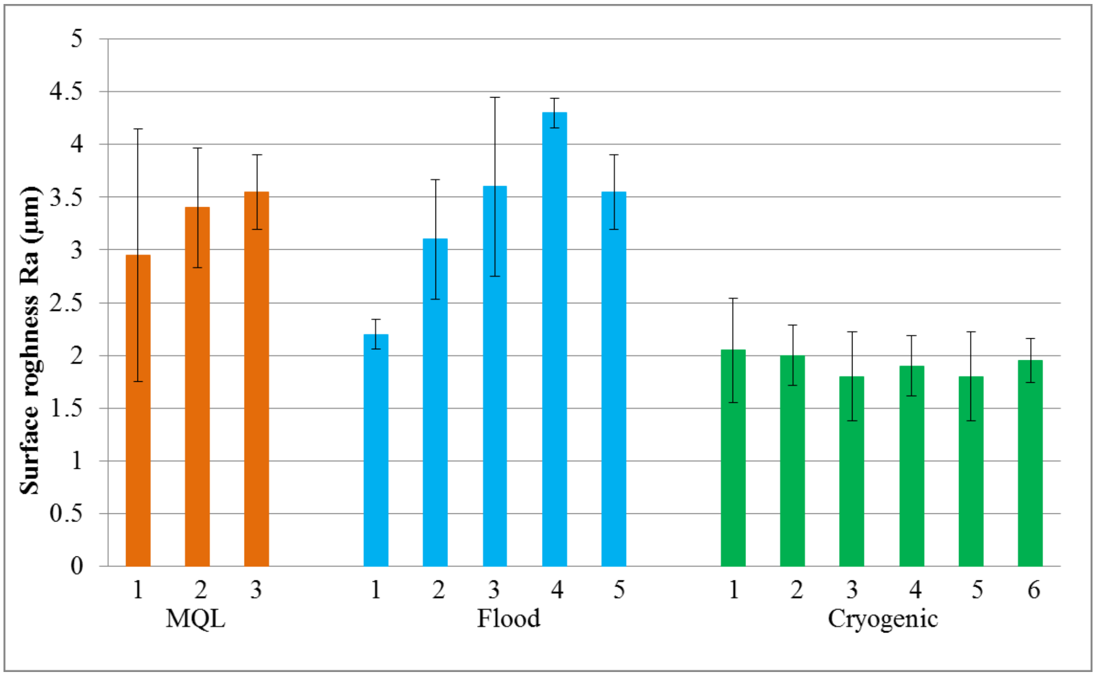

Figure 2: Surface roughness measurement results from drilling experiments for each machining environment

Analysis of the surface roughness also revealed that cryogenic cooling has produced smaller variation in surface roughness resulting in lower standard deviation from mean value. This is specifically important when predictable surface roughness is required in mass production.

As shown in figure 2, only three holes were drilled under MQL environment. Excessive heat generation and welding of the chips onto the cutting tool, forced to terminate the drilling experiment for MQL environment as depicted in figure 3. The flood cooling environment allowed for 5 holes to be drilled whilst it was 6 for cryogenic environment. SEM micrographs of the cutting tool, illustrated in figure 4, indicated that adhesion and diffusion were the dominant tool wear mechanism irrespective of machining environment. Figure 4, demonstrates the tip of the drills used for experiments under different machining environments. The workpiece material is adhered onto the tip and the rake face of the tool. Similar observations were reported by Bordin et al. [12] in turning additively manufactured titanium alloy workpieces. Energy dispersive X-ray spectroscopy (EDAX) was performed and the diffusion of titanium and aluminum to the cobalt-tungsten carbide cutting tool material was confirmed.

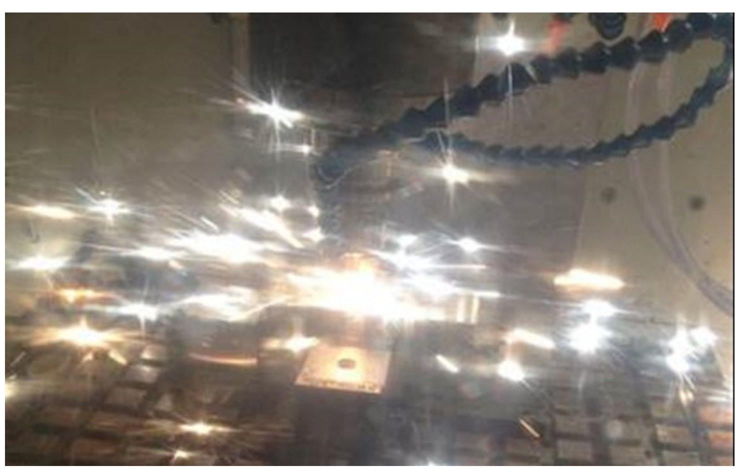

Figure 3: Excessive heat generation during drilling experiment using MQL

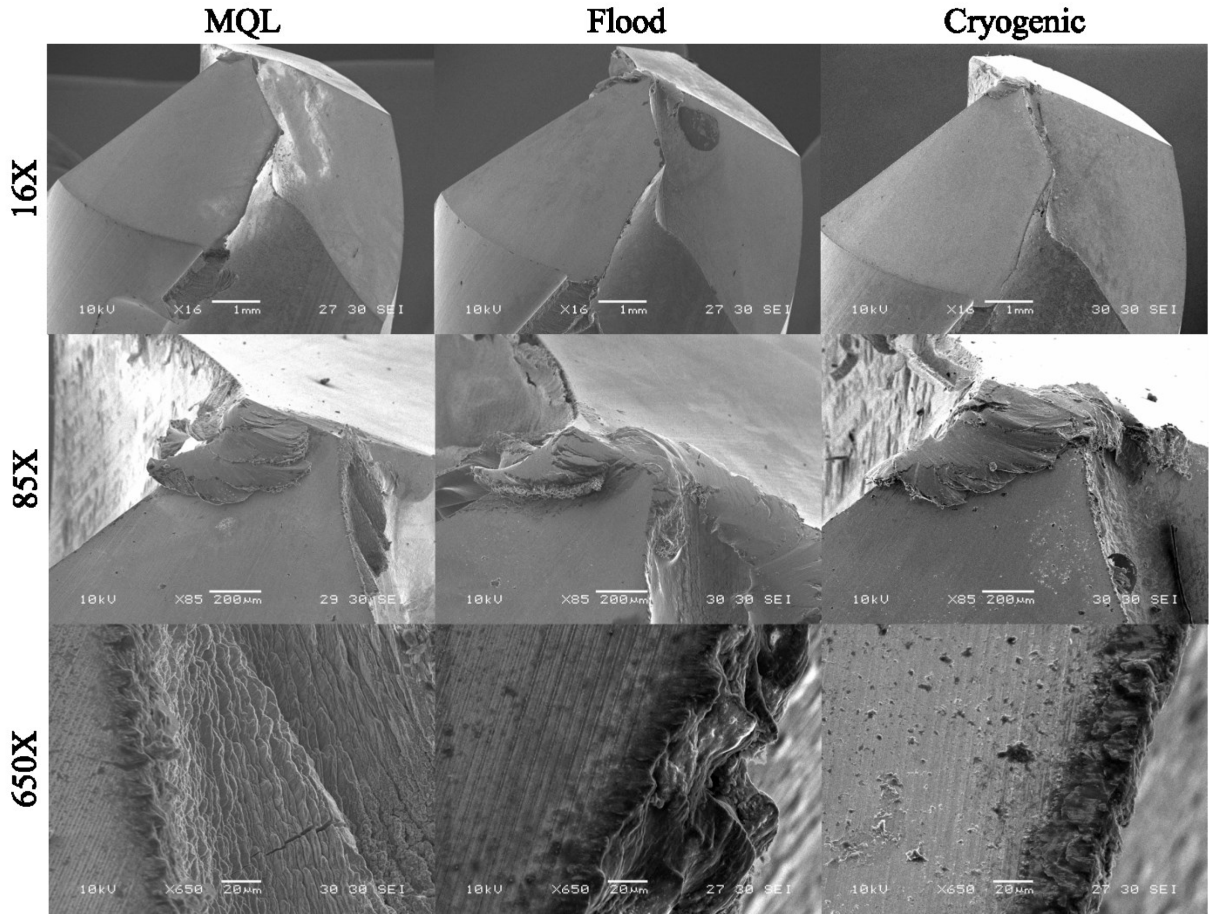

Figure 4: SEM micrographs of the tip of drill bits used for drilling experiments indicating adhesion of workpiece material onto the drilling tool

Further investigation revealed that chipping has taken place on the periphery of the drill in MQL environment (figure 5). Adhesion of the workpiece material onto the rake face of the drill has resulted in weakening of the cutting edge. Under the extreme cutting condition, this has led to chipping of the cutting edge. Excessive adhesion and smearing of the workpiece material onto the flank and rake face were detected on the periphery of the drills irrespective of the machining environment. As shown in figure 5, cryogenic cooling has reduced the adhesion and diffusion wear mechanisms but failed to prevent this phenomenon.

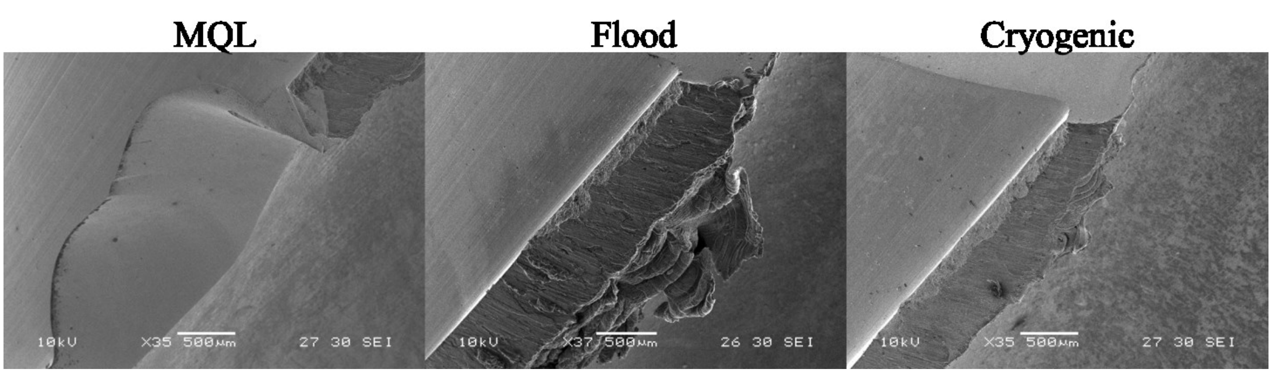

Figure 5: SEM micrographs of the periphery of the drilling tools; chipping of the tool from MQL experiment and adhesion of workpiece material onto the tools from flood and cryogenic cooling.

This investigation indicated the importance of chip evacuation, temperature control and lubrication in drilling titanium. The MQL uses atomized particles of lubricant dispersed through a stream of pressurized air. Whilst it can sufficiently lubricate the cutting zone, its capabilities in heat removal and chip evacuation is limited. On the other hand, using cryogenic cooling can significantly reduce the temperature at the cutting zone and reduce the chemical affinity between the tool and workpiece material. However, high cutting pressures, friction and heat result in adhesion of titanium onto the cutting tool. Similar observations were reported by Bermingham et al. [9] where the authors recommended selecting optimum cutting parameters is more important than cooling condition. In order to realize high speed drilling of titanium, further research in cutting geometry, inert coating with low friction characteristics and advanced coolant/lubricants are necessary.

5. Conclusion

Drilling is one of the important operations where it usually takes place when the components are semi-finished or prior to assembly. In this study cryogenic drilling of Ti-6Al-4V titanium alloy was numerically and experimentally compared with conventional flood cooling and MQL. The investigations revealed that cryogenic cooling can substantially reduce cutting temperature and control adhesion and diffusion wear resulting in 20% increased tool life. The cutting temperature was reduced from 1150ºC in flood cooling to 725ºC in cryogenic machining environment. Furthermore, on average 43% reduction in surface roughness was achieved using cryogenic cooling. This improvement is partially due to reduced tool wear as a result of cryogenic cooling.

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